Renewable and Sustainable Energy Reviews 39 (2014) 1185–1199

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Heat resources and organic Rankine cycle machines

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ARTICLE INFO

Article history:
Received 13 August 2012
Received in revised form
1 June 2014
Accepted 19 July 2014
Available online 9 August 2014

Keywords:
Organic Rankine cycles
Biomass
Geothermal
Solar
Waste heat
OTEC

ABSTRACT

Various Rankine cycle architectures for single fluids and other improved versions operating with ammonia/water mixture are presented in this paper. Untapped heat resources and their potential for driving organic Rankine cycles are outlined. The nature – state and temperature of the heat source significantly influences the choice of the type of organic Rankine cycle machine. The temperature appears as a critical parameter during the selection process. Modules differ from one another from technology, size and cost viewpoints. The investment cost of an ORC project includes machine, engineering, system integration, capital costs, etc. and is closely linked to the application.

Contents

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http://dx.doi.org/10.1016/j.rser.2014.07.139

1. Introduction

The growing concern over the future depletion of fossil fuels reserves and the dramatic destruction of our environment have brought to the light the organic Rankine cycle (ORC) technology for low-grade heat recovery. Governments, industries and researchers have shown past few years a lot of interest for this technology. This explains the intense activity observed in this field. Capture and conversion into electrical power of various low/medium-temperature heat resources from biomass combustion in CHPs [1–4], industrial processes [5–7], ocean warm layers [8,9], sun's radiations [10–13], hydrothermal and engineered geothermal (EGS) systems [14–18], and more recently abandoned oil fields [19] has become an important topic. The organic Rankine cycle technology is favoured by following features [20,21]:

- Adaptability to various heat sources
- Proven technology with great maturity
- Less complexity and less maintenance
- Possibility of small scales
- Distributed generation system
- Low investment and maintenance costs
- Good market availability and well known market suppliers

The paper is divided in several parts. First, a definition of the Rankine cycle is given along with improved or proposed versions and, then follows a review of various heat resources and potential. Third part deals with organic Rankine cycle machines as they are present on the market. Final section is a summary and comparison of organic Rankine cycle applications.

2. Rankine cycle architectures

2.1. Single fluid Rankine cycles

2.1.1. Basic Rankine cycle

The Rankine vapor power cycle is one of various cycles that were developed for power generation. William John Macquorn Rankine is the Scottish engineer who along with Rudolph Clausius and William Thomson developed the scientific background of this cycle. The basic Rankine cycle made up of four components (pump, boiler, turbine and condenser) was later modified to give birth to more advanced and efficient Rankine cycle configurations [22]. Typically, water is used as the working fluid. However, small systems are made possible only with organic fluids like refrigerants and hydrocarbons in so called "Organic Rankine Cycles". Organic working fluids are suitable at low (<150 °C) and moderate (150–300 °C) temperatures where water fails for economic and technical reasons [23,24]. The ideal theoretical Rankine thermodynamic cycle consists of four processes as depicted in Fig. 1 [22]:

- Process 1–2: isentropic expansion in a turbine or expander
- Process 2–3: isobaric heat rejection in the condenser
- Process 3–4: isentropic compression by a pump
- Process 4–1: isobaric heat addition in a boiler

In organic Rankine cycles, efficiency improvements can be achieved through regeneration by integration of regenerator or feedliquid heaters or by operation taking place above the critical point in transcritical or supercritical cycles [25–28]. The Clausius–Rankine cycle constitutes the basic cycle for vapor-based heat engines and is widely used for power generation in thermal power plants fueled by coal, gas, oil or nuclear materials. However, the environmental concerns and the future depletion of fossil fuels resources, have in recent years directed the attention of the scientific community towards more environmentally friendly fuels such as solar energy, biomass, warm surface seawater, geothermal fluids and waste heat. These fuels provided they are upgraded or an appropriate cold sink is found could be exploited to drive an organic Rankine cycle system.

2.1.2. Superheated cycles

The operation and the performances of the power producing device are greatly influenced by the thermophysical properties (temperature, vapor density, enthalpy, etc.) of the working fluid. Fluids with high density and high enthalpy will be preferable. Three groups of fluids are widely distinguished (wet, dry and isentropic). Wet fluids exhibit high boiling points and a negative slope ($dT/ds<0$ on the saturated vapor line). Water and ammonia are wetting fluids. Dry fluids present a positive slope and isentropic fluids an infinite slope. Superheating a wetting fluid increases the evaporator average temperature and the cycle efficiency and eliminates droplets during the expansion process [29]. The superheating takes the saturated vapor (state 4) to state 4′ and this results in an increase of the power output ($h_{1'}-h_{2'}>h_1-h_2$) without moisture as the end of the

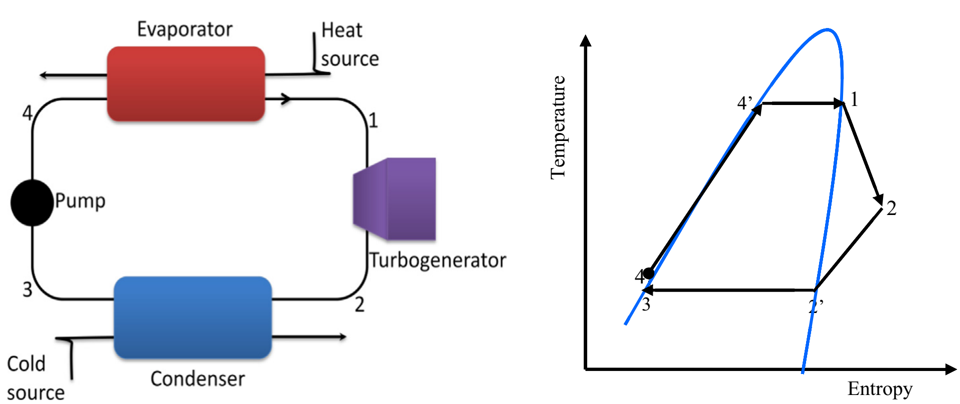

Fig. 1. The basic Rankine cycle.

expansion process. This guarantees a safe operation of the turbine. Drying fluids do not require superheating as the expansion process takes place in the superheated region. Superheating would not have any benefit for the cycle as shown by Hung et al. [7]. Performances of cycles with isentropic fluids are not affected by superheating. Fig. 2 shows different expansion cases.

2.1.3. Transcritical/supercritical Rankine cycles

Subcritical Rankine cycles operate at pressures below the critical point. High pressure operation leads to better cycle efficiency with the increase of the evaporator temperature. A simple Rankine cycle works within two pressure values: evaporator pressure (highest) and the condenser pressure (lowest). The average temperatures at both pressures constitute the boundaries for the cycle system efficiency, considering the Carnot theory. Critical pressure (of the working fluid) found within the max and the min cycle pressures, the cycle is "transcritical" (see Fig. 3). Transcritical steam cycles show high efficiency, up to 40% but require specific materials and high safety precautions owing to very high pressures. Supercritical Rankine cycles as defined by Feher [30] are cycles for which heat exchanges take place out of the saturation dome, including condensation (Fig. 3). But this configuration has not been investigated till now neither with steam nor with organic fluids. The terms "transcritical" or "supercritical" are used for both configurations and for many authors mean cycle with evaporation above critical point.

Transcritical/supercritical organic Rankine cycles use organic fluids with low boiling point and low critical temperature, e.g. CO_2, R290, R134a, R32, etc. Recent works demonstrate the interest for this configuration [26,27,31]. Drowned conclusions are:

- A shift from sub- to transcritical operations does not change the cycle efficiency significantly, close to 8%.
- Heat exchangers are more efficient when used in transcritical cycles.
- Transcritical cycles require additional safety precautions because of excess pressures, increasing therefore the system's cost.

Specifically, there is an increasing interest in using CO_2 as working fluid for vapor compression cycles as well as for power generation in nuclear plants, waste heat recovery systems as well as in solar thermal power installations [32–34]. Carbon dioxide has many advantages: it is abundant and environment-friendly, non-flammable, non-toxic, cheap and its thermophysical properties well known.

2.1.4. Rankine cycle with internal heat exchanger

As demonstrated earlier, isentropic and dry fluids are suitable for ORC cycle systems. With such fluids, the expansion process takes place in safe conditions in the expander. A regenerator could be integrated into the cycle as shown in Fig. 4 to increase the cycle thermal efficiency, especially when drying fluids are used. The requirement of the uses of a regenerator is that the temperature of the vapor leaving the expander be substantially higher than the condensing temperature. Vanslambrouck et al. [35] showed the existence of a limit under which a regenerator is useless, this limit is close to 100 °C.

2.1.5. Rankine cycle with reheating

A typical Rankine cycle operates with water which is a wet fluid, and superheating it has the advantage of protecting the turbine and using a second turbine needs to superheat the low pressure fluid coming out from the first stage turbine. A practical solution used in modern steam power plants is the integration of a two-stage turbine with a reheat in between. A schematic of a reheat regenerative Rankine cycle is shown in Fig. 5. The working fluid is expanded twice, 3–4 and 5–6. Several stages could be used.

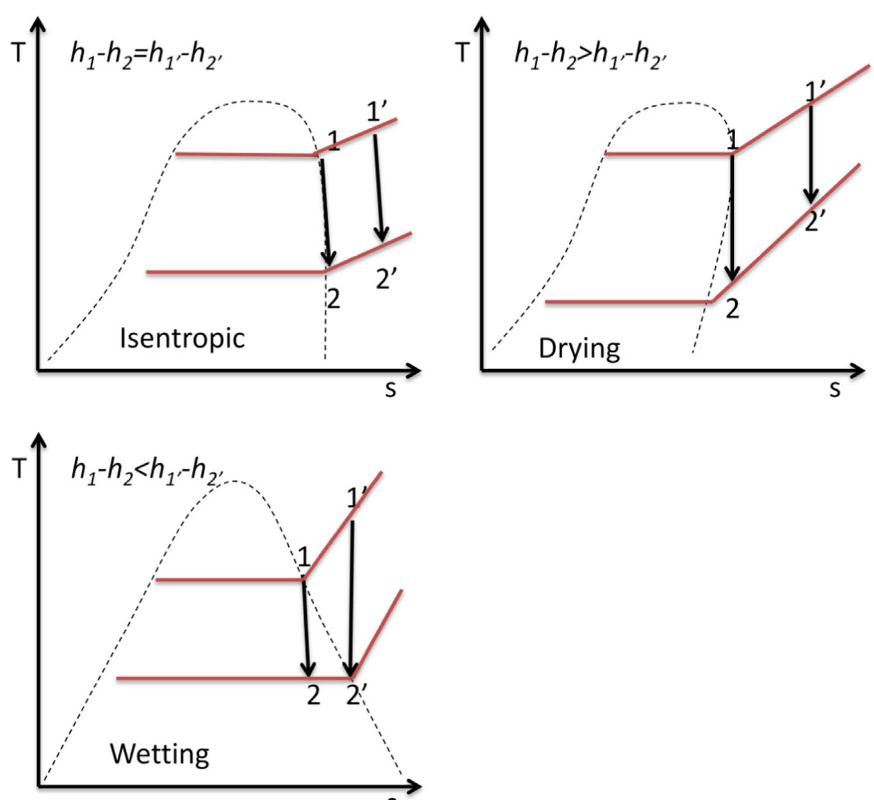

Fig. 2. Expansion process with different types of fluids.

This configuration has not yet been investigated with organic fluids.

2.1.6. Rankine cycle with integrated feedliquid heaters

Fig. 6 shows Rankine cycles with feedliquid heaters. In an open feedliquid heater, two fluid streams from the pump (2) and the extracted fluid (6) from the turbine mix up; this provides higher temperature fluid in the evaporator. A closed feedliquid heater allows heat from the extracted fluid (7) to be transferred to the feedliquid (2) without any mixing taking place. Feedliquid heaters improve the performance of the cycle and a better control of the fluid flow. This was demonstrated by Mago et al. [25] with organic fluids. Srinivas et al. [36] studied the effects of multiple feedwater heaters on the performance of a steam power cycle and found that maximum efficiency is obtained with the first feedliquid heater and the extent of the increment with successive feedliquid heaters is lower.

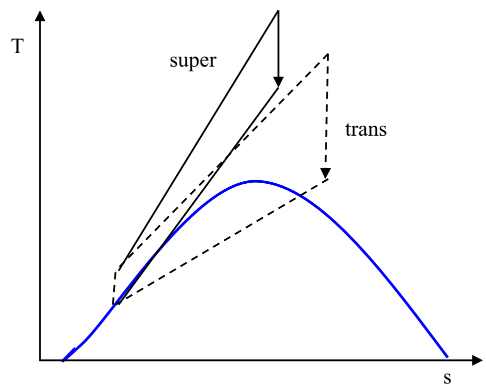

Fig. 3. Trans- and supercritical Rankine cycles.

2.2. Binary fluids Rankine cycles

There are few low-temperature power cycles using fluid mixtures as working fluid instead of single components fluids. Fluid mixtures incorporation in Rankine cycles displays temperature increase during the evaporator isobaric heat exchange. A binary mixture of water and ammonia is well known and the temperature glide with a mass fraction of 0.7 and a pressure of 2.5 MPa is 94 °C [37]. Robertson and Maloney in 1953 were the first to propose a cycle with binary mixture. But the proposed cycle did not give satisfactory results and was abandoned. In the 1980s the investigations resumed and improved versions appeared in literature.

The Maloney and Robertson cycle adds to a traditional Rankine cycle a fluid mixture and a flash tank. A schematic of the cycle is depicted in Fig. 7. A boiler delivers a vapor rich in ammonia (6). This vapor is then superheated (7) and expands in a turbine. The turbine exhaust (8) is reunited with the weak solution from the

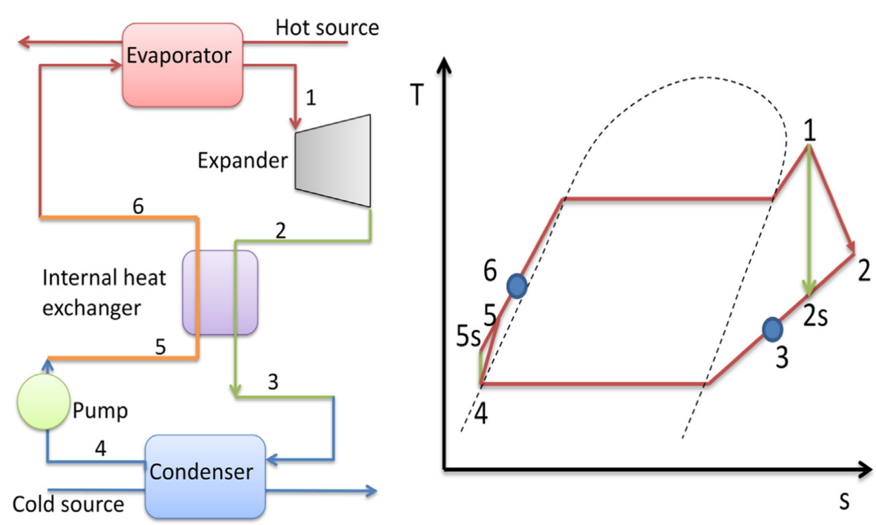

Fig. 4. Rankine cycle with integrated regenerator.

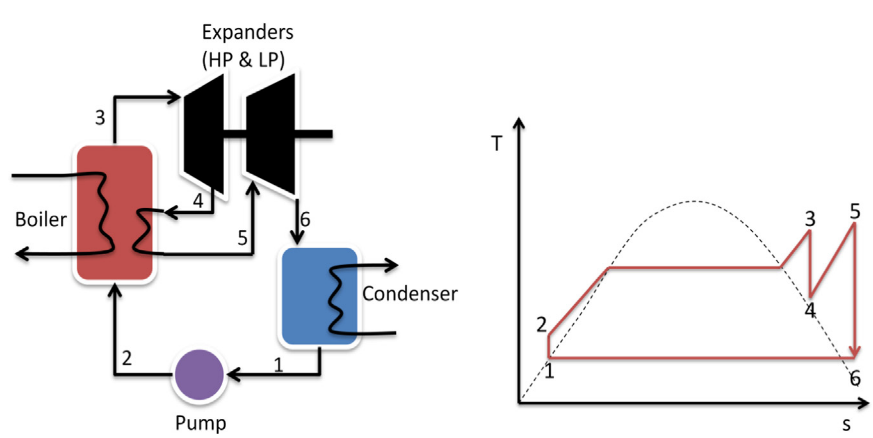

Fig. 5. Rankine cycle with reheater.

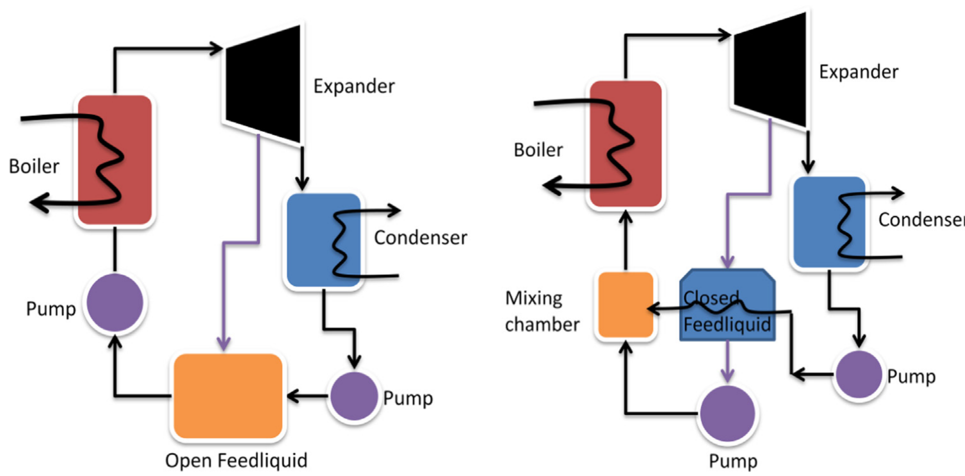

Fig. 6. Rankine cycle with feedliquid heater.

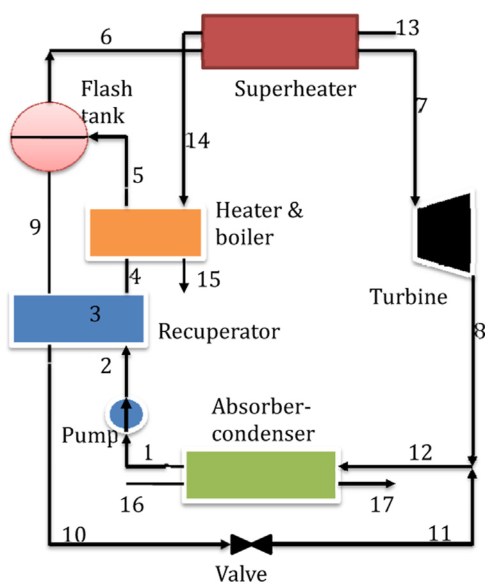

Fig. 7. The Maloney and Robertson cycle.

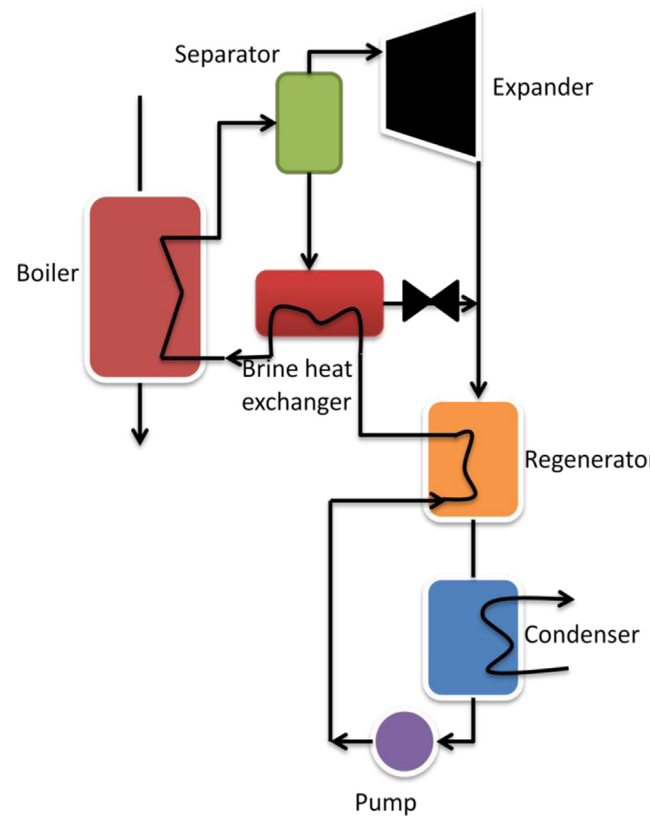

Fig. 8. The Kalina cycle.

distillation unit (11) and is used to absorb the rich vapor in ammonia to regenerate the basic solution (1). The basic solution is then pumped to a high pressure and then heated and partially boiled before entering the flash tank (5) to complete the cycle. Hot (13) and cold (16) fluids are used as the heat source and sink, respectively. Maloney and Robertson compared their cycle to the Rankine cycle and concluded it had no advantage and stopped their investigations [38].

A.I. Kalina continued the work on absorption power cycles and came out with several cycle designs [39]. The first Kalina cycle was presented in 1983 [40]. A separator, a recuperator and an absorber are incorporated into a simple Rankine cycle to form the new cycle. A typical Kalina cycle is shown in Fig. 8. The ammonia–water mixture is heated in the evaporator. Before the turbine, the ammonia-rich vapor is separated from the liquid phase in a separator. Afterwards, the ammonia-rich vapor expands in the turbine. The molecular weight of the ammonia is close to that of the water and therefore it is possible to use normal back-pressure turbines. After the turbine, the vapor and liquid phases are merged together and condensed in the condenser. Because of the change in the mixing ratio, the evaporation temperature increases continuously in the two-phase region while it decreases during condensation. The recuperators included are used for residual heat management within the cycle. Thermal efficiencies 10–60% higher than comparable steam plants were reported [37]. DiPippo [41] compared performance of existing geothermal plants using the second law of thermodynamics. The plants under investigation included the Husavik plant. Under identical conditions, the calculated performance difference is about 3% in favor of a Kalina cycle. Bombarda et al. [42] compared Kalina and Rankine cycles in waste heat recovery application. Kalina design produced more power but was less cost-effective compared to organic Rankine cycle because of the high evaporator pressure and large evaporator surface requirements.

Uehara et al. [43] studied various cycles for ocean thermal energy conversion (OTEC) plants. Kalina cycle operating with very low temperature (~25 °C) showed poor performance of the heat

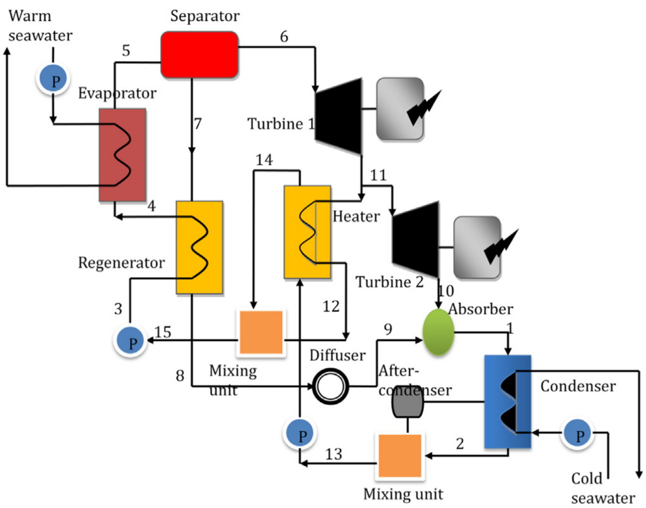

Fig. 9. The Uehara cycle.

exchangers. An improved version of Kalina cycle was then proposed and named "Uehara cycle". It integrates a separator, two turbines, two regenerators, two mixing units, a diffuser and an after-condenser. A layout of a typical Uehara cycle is shown on Fig. 9. A prototype was tested [44] and according to the designer, considering 28 °C warm seawater and 6 °C cold seawater, the cycle yields 5.4% thermal efficiency, that is 10% higher than Kalina and 30% larger than Rankine operating in similar conditions with ammonia [43]. The system as described is very complex in comparison with Kalina and Rankine cycles.

Goswami proposed a combined power/cooling cycle [45,46] which combines Rankine and ammonia-absorption refrigeration cycles (Fig. 10). The combined cycle is designed to primarily produce power and could be cost effective if used to recover low-temperature heat. A prototype was tested at the University of Florida [47]. Operating conditions were further investigated by several authors [48–51]. High power output and high cooling capacity cannot be reached simultaneously with the cycle and the designer should set an operating condition.

3. Heat resources

Solar, biomass and geothermal energy considered as renewable and clean energy sources, and industrial waste heat can potentially cover the world electricity demand. However, conventional power generation techniques cannot efficiently convert the low-temperature heat generated from these sources into electrical power. Hence, large amounts of low temperature heat are simply wasted or unexploited.

3.1. Biomass resource

The term biomass refers to all organic matter that is derived from plants as well as animals. Biomass resource considered as renewable energy source include wood and wood wastes (lignocellulosic products), agricultural crops and their waste by-products, municipal solid waste (MSW), animal wastes, wastes from food processing industry, aquatic plants and algae [52]. Most of bio-energy is produced from wood and wood wastes, followed by MSW, agricultural waste, and landfill gases [53]. Wood is derived from trees which can be grown and fast growing species can be harvested every few years. Waste wood are available in the form of sawdust, bark, board ends, etc. Agricultural residues include cotton stalks, wheat and rice straw, coconut shells, maize and jowar cobs, jute sticks, rice husks, etc. A certain number of crops are grown for energy purpose: sugar cane, sugar beets, grains, cassava, sunflower, jatropha curcas, etc. Biomass as renewable energy option presents many advantages among which the possibility of delivering energy in solid, liquid and gaseous forms to meet a variety of energy needs including electricity generation, space heating, process heating and vehicle motion. Biomass supplies most of energy needs of developing countries. It accounts for significant share of energy balance in Bhutan (86%), Nepal (97%), Nigeria (85%), Kenya (76%), Ghana (64%) and Cote d'Ivoire (75%) [53,54]. The share of biomass in developed countries in significantly low, about 3.5% in the EU and 2.7% in North America [54].

Conversion routes have been developed to transform raw biomass material into useful energy forms. These include bio-chemical, chemical and thermo-chemical processes leading to different products: bio-alcohols, bio-diesel, bio-gas, syngas, etc. The latter products and raw materials such as wood, wood waste, compressed husk, straw and other solid residues can be burned to generate heat. Suitable biomass products for biomass organic Rankine cycle systems are solid fuels: logs, sawdust, woodchips, pellets or compacted agricultural residue easily burned in boilers.

The global biomass potential is estimated at about 3500 EJ/year [53]. Most of the biomass resource is located in South America, Sub-Sahara Africa, the C.I.S and Baltic States, Oceania and North America and is unexploited. The total global forest area is closed to 4 billion hectares or 30% of total land area and is distributed as follows: America (38.9%), Europe (25.3%), Africa (16.1%), Asia (14.5%), and Oceania (5.2%) [53].

3.2. Ocean resource

Oceans cover about 70% of the planet Earth. The source of ocean thermal energy is the Sun. Oceans act as a huge natural solar thermal collector and heat reservoir, absorbing and storing solar

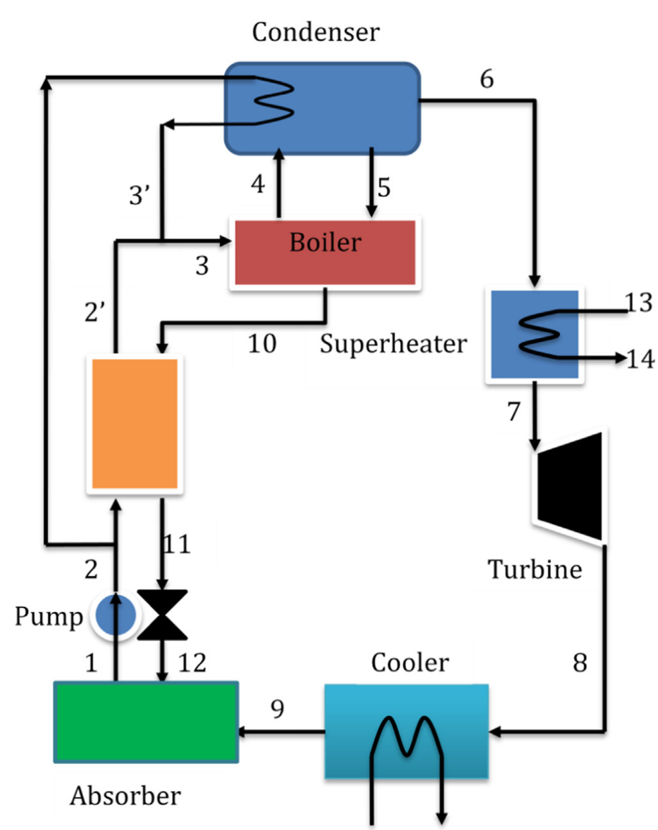

Fig. 10. The Goswami cycle.

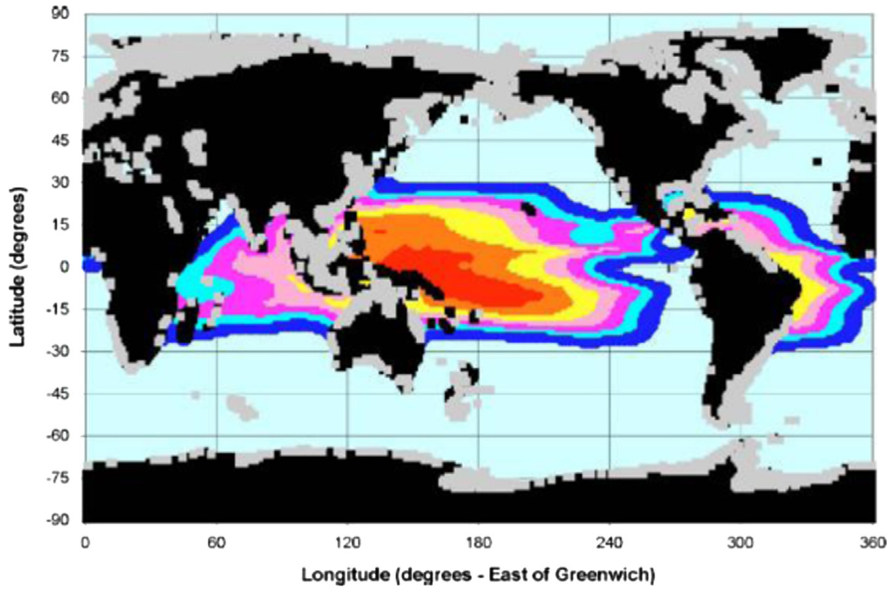

Fig. 11. A map of the OTEC resource.

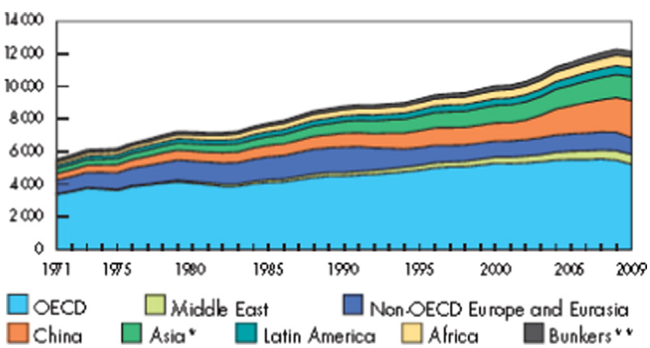

Fig. 12. World total primary energy supply.

energy in the surface seawaters in a layer of about 50–100 m thick at an approximate temperature of 26–31 °C all year long. Below the warm layers, the temperature falls gradually with depth reaching a temperature of 2–7 °C at 800–1000 m. Below, the temperature decreases very slightly to the ocean bottom at depth around 4000 m [21,55]. The natural thermal stratification occurring in oceans produces huge amount of untapped energy. Vertical ocean seawater temperature distribution has been measured in many regions around the world, and in order to be exploited the minimum temperature difference between the ocean surface and deep layers should be about 22–27 °C [9]. These temperature gradients are found in tropical oceans near the Equator – see Fig. 11 [8,9]. On a daily basis, 60 million km^2 of tropical oceans absorb an average of 10^{15} MJ of solar radiation - equivalent to the amount of heat obtained by burning some 200 billion barrels of oil [55].

The energy stored in the oceans upper layers can be extracted using the OTEC (ocean thermal energy conversion), a technology developed for this purpose from the original idea of the French physicist d'Arsonval (1881). The OTEC principle is simple and similar to that of a conventional steam Rankine cycle [21]. Major components of an OTEC system are: evaporator, turbine, working fluid pump, condenser, warm seawater pump and deep cold water pump. Warm surface water flowing in the evaporator transfers the heat to a working fluid having a low-boiling point of about −30 °C (such fluids are Propane, Ammonia, etc) – the working fluid then evaporates and expands in a turbine coupled to an electric generator. The cold exhaust vapor from the turbine is subsequently liquefied using deep cold water from bottom layers in the condenser. The liquid fluid is pumped back to the evaporator to complete the cycle. Apart from Rankine closed cycle, Kalina as well as Uehara cycles can be also implemented.

Recent concerns about the environment, the long term energy supply, the growing energy demand as well as the steady increase in the cost of primary energy have rekindled the enthusiasm for renewable energy from ocean origin. The natural collection and storage capacity of oceans eliminate problems associated with the fluctuations of the resource that marks most of renewable energy systems. Though oceans cover about 70% of the Earth's surface, the entire ocean surface may not be suitable for energy exploitation. Favorable sites for OTEC should fulfill following criteria: high temperature difference, low velocity currents, no storms and nearness to the market for derived products [56]. The magnitude of the technically feasible potential of this technology has not yet been extensively evaluated. A study conducted by Nihous [8] led to an estimate of the maximum steady-state OTEC electric power in the range of 3–5 TW.

3.3. Waste heat resource

The world energy demand is constantly increasing – see Fig. 12 [57], and this trend is expected to continue as more countries develop, i.e. India, China, Russia, Brazil, South-Africa, etc. Primary energy, mainly fossil fuels (oil, gas and coal) are used directly or refined and converted into heat, mechanical or electrical power for utilization in industrial, transport, and residential sectors. These resources have been used for centuries to sustain the economic growth, and the reserves are becoming progressively depleted while our environment is increasingly harmfully affected by the unsustainable and inefficient combustion of these fuels.

In the transport sector, typical internal combustion engines (ICE) – diesel, gasoline and heavy fuel engines have an efficiency of about 30–35%, which means that more than 60% input energy is wasted in the form of heat at a temperature of 300–400 °C through exhaust gases and at lower temperature by cooling water [58]. This is observed in cars, trucks, and ships. Considering the number of cars on roads and the number of ships sailing in oceans, and taking into account the growth observed in the transport

sector, large amounts of heat will continue to be dumped in the environment in the proportion close to 2/3 of that globally used.

Industrial processes as well as thermal engines and mechanical equipments produce large amounts of waste heat. Exhausts discharged to the environment do not only contain high exergy value but also large quantities of pollutants said responsible of the current global warming which has as consequences sea level increase, destruction of natural ecosystems, unpredictable weather, etc. Numerous reports show high potential for industrial waste heat recovery. Up to 70% of energy input in the manufacturing sector is lost in Canada [37]. In the US, industrial waste heat amounts to about 20–50% [59]. In the UK heat losses in the industrial sector could represent few tens of TWh [60]. Energy-intensive industries have been identified, and these include [59,61]: metal industry (iron, steel, copper, aluminum and glass), Cement and building material industry, food and beverage processing industry, pulp and paper industry, electricity industry, petroleum and chemical industry.

Liquid and solid streams, hot air and flue gases, pressurized hot water, wastewater and exhaust vapor are typical waste heat carriers [37]. Waste heat sources are grouped in three categories based on temperature level [21]: low ($<230\,^{\circ}$C), medium (230–650 °C) and high ($>650\,^{\circ}$C). The global total primary energy supply is approximately 500 EJ [62], at least one third could be rejected to the atmosphere by a variety of energy conversion processes and appliances having limited efficiency due to thermodynamic considerations. Various technologies have been developed for waste heat recovery in view of fuel efficiency improvement and pollution reduction. The applicability of these technologies is based on the tradeoffs between the operating temperature and the waste heat temperature level. For instance, thermodynamic power cycles, mainly steam Rankine and organic Rankine cycles are successfully implemented to recover high and low/medium temperature waste heat, respectively for power generation; thus increasing plant efficiency by about 5%.

3.4. Geothermal resource

The geothermal energy – i.e. thermal energy from the Earth originates from the decay of radioactive isotopes and partly from the relic released about 4.5 billion years ago during globe's formation. Geothermal heat appears in the form of dry rock, steam and pressurized water. Classification is performed either by temperature level or by heat transfer mode [63]. High-temperature ($>180\,^{\circ}$C) systems are associated with recent volcanic activities and mantle hot spot anomalies, intermediate (100–180 °C) and low-temperature (less than 100 °C) systems found in continental settings and supplied by radioactive isotope decay and water circulation along deep penetrating fault zones. Based on heat transfer geothermal systems are classified as: convection-dominated (liquid and vapor), conduction-dominated (hot rock and magma) and mixed systems. Convective or hydrothermal resources and enhanced geothermal systems (EGS) based on hydraulic stimulations and advanced well configurations are most exploited geothermal systems.

Technologies for geothermal resource exploitation include those for electrical power generation (well known: flash steam, Kalina cycle, binary organic Rankine cycle, etc) and those for direct uses i.e. applications requiring heat such as district heating, cooling and heating of buildings/processes, aquaculture, etc.

Geothermal energy is considered as clean, abundant and renewable energy resource – the wells/heat reservoirs are continually restored by natural heat production. The Earth's heat flow – i.e. the amount of heat released into space from the interior through a unit area in a unit of time, varies from place to place on the surface and with the time at a particular location. 65 mW/m^2 was measured values on continents, and 101 W/m^2 on the ocean floor. This leads to a global earth's heat flow rate of 1400 EJ/yr (315 EJ/yr emitted by continents) – what is more than twofold the world total energy supply. Global resource assessment was carried out at different depths: 42.67×10^6 EJ/yr down to 3 km, 139.5×10^6 EJ/yr down to 5 km, and within 10 km depth 403×10^6 EJ/yr [64]. The global technical potential for electricity generation is in the range 117.5 EJ (3 km)–1108.6 EJ (10 km depth) [64].

3.5. Solar resource

Solar energy is the most abundant source of energy on Earth. It refers to any phenomenon that bears its origin from the energy radiated by the Sun and can be harnessed as useable energy, directly or indirectly. In this respect, wind, ocean thermal, hydropower and biomass energies are derived forms of solar energy. The present work deals only with direct use of solar irradiance in the form of light or heat.

The Sun is a sphere of intensely hot gaseous matter with a diameter of 1.39×10^9 m. It is the site of fusion reactions which turn hydrogen into helium. Its surface temperature is close to 5800 K, and at its centre is much higher. Solar irradiance is spread over wavelengths in the range 0.25–3 μm. The analysis of the solar radiation spectrum shows 40% visible light, 10% UV and 50% infrared radiation. The solar irradiance reaching the Earth is divided into beam radiation coming from the Sun's disk and the diffuse radiation coming from the whole sky except the Sun's disk. The intensity of the solar irradiance is influenced by the proportion of various atmospheric constituents (aerosols, clouds, water vapor, etc.) and varies with both time and location. Yearly average value of solar radiation reaching the Earth's surface varies from 60 W/m^2 at higher latitudes to about 250 W/m^2 in desert areas [65].

Conversion of solar energy into electricity or heat is possible, but depends upon the technology, economics, and location suitability for implementation. The potential of solar energy is enormous compared

Table 1
Solar energy technologies [65].

Size of the application	Active solar			Passive solar
	Photovoltaic systems	Solar thermal systems		
		Electric	Heating	
Centralized (>200 kW)	Concentrating PV (CPV) and utility-scale PV	Concentrating solar power (CSP)	District water heating system	
Large-scale distributed (>20 kW)	Commercial BIPV	Micro solar CSP	Commercial hot water systems	
Small-scale distributed (<20 kW)	Small commercial and residential BIPV	Micro solar CHP	Residential water heating systems	Heating and cooling
Off-grid applications	Stand alone systems for remote applications, solar home systems			Day lighting

to the actual energy demand and other renewable energy sources such as geothermal, wind, ocean and biomass [65]. The global solar energy potential has been assessed by various authors and organizations and data are available from many sources. The theoretical potential for energy purposes is estimated at 3.9×10^6 EJ/yr [64]. The technically feasible potential that is the proportion of theoretical potential that can be harnessed by available technologies varies across the Earth and depends on many factors – mainly local meteorological conditions, land availability, and technology. Table 1 lists most solar technologies. Photovoltaic systems convert solar irradiance directly into electricity while solar thermal collectors convert it into heat at different temperature levels for a variety of energy service applications. Low-temperature solar collectors (<80 °C) are used for domestic hot water and space heating, medium-temperature ones are designed to operate at 80–300 °C – temperature range desired for heating processes, and for power generation, heliostats, parabolic troughs and linear Fresnel reflectors operating above 300 °C possess the ability to generate high temperature materials (such as molten salts) suitable to drive a steam cycle [66]. Based on the maturity of available solar technologies, the global solar technical potential was estimated at 1,575–49,837 EJ depending on assumptions – this represents 3–100 fold the world total primary energy supply [64]. Regional assessments show that Middle East, Africa and America have very high potential.

4. ORC machines

4.1. Typology of organic Rankine cycle machines

An ORC machine has a minimum number of components consisting of a power-producing device, a generator, a feed pump, an evaporator, a condenser, a recuperator and control systems – some market available machines are shown in Fig. 13. Few products and specifications are given in Table 2. ORC solutions are designed to produce power from a kW up to few MW. Market survey showed a great diversity of machines in terms of size, expansion device technology, heat source temperature handled, maturity, market availability, type of working media and cost. ORC machines are available from an increasing number of manufacturers – a non-exhaustive list is given in Table 3. The machine can be tailored according to the customer's specifications or bought ready from suppliers. Once on the site, the machine is adapted to the heat source. Classifications developed here below are then possible.

4.1.1. Heat source temperature

Here three main types of machines are distinguished: low temperature (<150 °C), Medium temperature (150–300 °C), and high temperature (>300 °C). Low-temperature machines will be used to recover geothermal or low-grade waste heat. BEP Europe [67], Opcon [68], Ormat [69] and Electratherm [70] propose solutions in this range. BEP Europe produces machines that could recover waste heat from 80 °C to 150 °C. Electratherm adapt its products in the range 60–120 °C. Medium temperature machines are suitable for recovering biomass combustion heat. Turboden has a series of machines in this range for CHP applications [71]. High temperature will be well adapted to recover heat from gas and diesel engines, flares and waste heat. Triogen machine [72] falls in the last category of high temperature. It requires heat of at least 350 °C and 900 kW thermal input to produce approximately 165 kWe.

4.1.2. Size

Very different machines available on the market have different sizes and can be classified as follows [35]: very small (<10 kW),

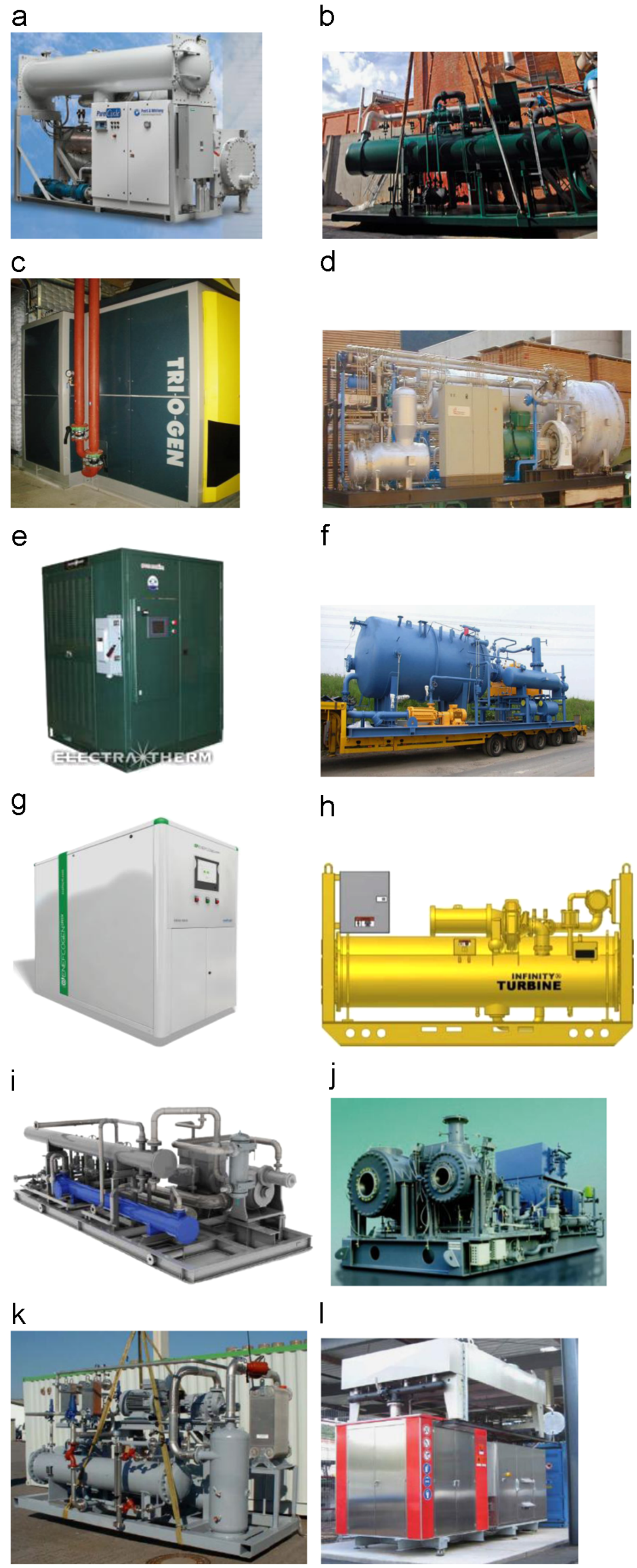

Fig. 13. Few ORC machines. (a) PureCycle280 (UTC), (b) Opcon module, (c) Tri-O-Gen module, (d) Turboden module, (e) Electratherm Green Machine, (f) Adoratec machine, (g) ENEFCOGEN module of Eneftech, (h) Infinity turbine® machine, (i) TAS® ORC module, (j) WOWGen® (WOW Energies), (k) Kohler und Ziegler Anlagentechnik GmbH and (l) LTi ADATURB GmbH module.

Table 2
Organic Rankine Cycle machines (from ORC manufacturers' websites and brochures).

Model	Manufacturer	Power output (kW)	Working fluid	Expansion device	Heat source /thermal oil /evaporating temperature (°C)	Cooling/condensing temperature (°C)	Electrical efficiency (%)
IT10	Infinity turbine	10	R134a	Screw	80–120	15–30	–
PureCycle®	Pratt & Whitney Power Systems	280	R245fa	Radial inflow turbine	80–120	–	–
TD4HR	Turboden	418		Turbine	150–275	25–35	18.2
TD12HRS	Turboden	1188		Turbine	206–305	25–35	23.6
TD27HR	Turboden	2740		Turbine	155–285	25–48	19.5
TD7CHP	Turboden	738		Turbine	240–300	60–80	18.4
Green Machine	Electratherm	50	R245fa	Twin screw	80–93	21	12
BEP module	BEP Europe	50	R245fa	Single and Z-screw	80–120	20	12
Triogen module	Tri-o-gen	80–165	Toluene	High speed turbogenerator	> 350	35–50	20–22
Calnetix series S, P, M	Calnetix Power systems	125	R245fa	High speed turbine	121	21	–
AD300 TF-plus	Adoratec	300		Turbine	155/245	60/80	17.03
AD625 TF-plus	Adoratec	625		Turbine	155/245	60/80	17.90
AD2400 TF-plus	Adoratec	2400		Turbine	160/250	60/90	17.35
ENEFCOGEN^{Plus} 05PLU-01	Eneftech	5	–	Scroll	160–200	20–50	–
PROMETHEUS-25	ENERBasque	20	–	–	80–90	10–25	4–8
EP60-ERS	Exergy	400–650	–	Radial outflow turbine	230–315	–	15–22

Table 3
Non exhaustive list of ORC manufacturers.

Companies	Website	Power output	Technology
Electratherm (USA)	www.electratherm.com	50 kW	Twin screw expander
Ormat (USA)	www.ormat.com/	0.250–20 MW	Turbine/n-pentane
Barber-Nichols Inc.(USA)	www.barber-nichols.com	15 kW to 6 MW	Turbine
Opcon Energy System AB (Sweden)	www.opcon.se	350–800 kW	Lynshom expander
Cryostar SAS (France)	www.cryostar.com	0.5–15 MW	turbogenerators
Tri-o-gen B.V. (Netherlands)	www.triogen.info	165 kW	High-speed turbine/toluene
Freepower (UK)	www.freepower.co.uk	60/120 kW	Turbine
Turboden (Italy)	www.turboden.eu	250–2200 kW	Turbine/OMTS, Solkatherm
GMK (Germany)	www.gmk.info	0.5–2 MW	GL-160, WL-220
Calnetix Power solutions (USA)	www.calnetixps.com	125 kW	Single stage radial inflow (turboexpander)
Durr Cyplan (Germany)	www.durr-cyplan.com	70/120/300/500 kW	Turbogenerator
ENER-G-ROTORS (USA)	www.ener-g-rotors.com	40–60 kW	trochoidal gear engine (TGE™)
Infnity turbine llc (USA)	www.infinityturbine.com	10–250 kW	Screw turbine
BEP Europe (Belgium)	www.e-rational.net	50–450 kW	Single screw expander
Eneftech (Switzerland)	www.eneftech.com	5–30 kW	Modular Scroll turbines
Kholer und Ziegler (Germany)	www.koehler-ziegler.de	ORC/50–200 kW Steam/150–1000 kW	Double screw expander
Ergion Gmbh (Germany)	www.ergion.de	–	–
Maxxtec AG/Adoratec Gmbh (Germany)	www.maxxtec.de, www.adoratec.com	300–1500 kW	Turbine/OMTS
Pratt & Whithney (USA)	www.pw.utc.com	280 kW	Reverse centrifugal chillers /R245fa
WOW Energies	www.wowenergies.com	0.5–25 MW	Gas expanders
ENERBasque	www.enerbasque.com	20–100 kW	–
Exergy (Italy)	http://exergy-orc.com	0.4–2.5 MW	radial-outflow-turbine
Termocycle (Netherlands)	www.termocycle.com/	50–250 kW	Turbine/R245fa
ENTRANS (Sweden)	www.entrans.se	50–500 kW	Flexibility (cooling/heating + power)
ENERTIME (France)	www.enertime.com	~1 MWe	Radial/axial turbines
Enogia (France)	www.enogia.com	5–100 kW	Micro-turboexpander
Verdicorp Inc. (USA)	www.verdicorp.com	20–180/20–310/20–105 kW	Oil-free turbocorp compressor
gTET (Australia)	www.g-tet.com	25/170/600 kW	High speed semi hermetic turbo-alternator

small (10–100 kW), medium (100–400 kW) and large (from 400 kW up to few MW). Very small systems would be adapted to cogeneration applications in buildings and additional power production in cars whereas small systems could be implemented to recovered heat from small internal combustion engines (ICE). Medium and large system sound suitable for industrial onsite additional power generation, distributed power generation in isolated areas or for grid connection. Large size modules are already available on the market and development focuses on small cost effective systems.

4.1.3. Working fluid

Usually, only four components are mentioned when recording components of an organic Rankine cycle. Unlike steam cycles which integrate water as working fluid, organic Rankine cycles use other fluids. These could be hydrocarbons (HCs), hydrofluorocarbons (HFCs), hydrofluoroethers (HFEs), ammonia, etc. A major obstacle hindering a quick development of organic Rankine cycle systems is the phase-out of some substances that could be used and the upcoming phase-out of some others. Industries are developing alternatives such as HFO (hydro-fluoro-olefins). Examples are: HFO-1234yf

Table 4
Cycles and fluid desired characteristics.

	Refrigeration cycle	Heat pump cycle	Organic Rankine cycle
Vapor/liquid density	High at the compressor suction port	High at the compressor outlet	High at the turbine inlet High at the pump inlet
Critical temperature	Low/moderate	Moderate/high	Moderate/high
Energy/exergy	High efficiency	High efficiency	High efficiency
Power	Low power consumption	Low power consumption	High power output and low pump work
Environmental impact	Low ODP, low GWP	low ODP, low GWP	Low ODP, low GWP
Materials and lubricants	Good compatibility	Good compatibility	Good compatibility
Safety	High safety level	High safety level	High safety level
Thermal stability	Good	Good	Good
Availability and cost	Good availability – low cost	Good availability – low cost	Good availability – low cost

Figure: Cycles and fluid desired characteristics.

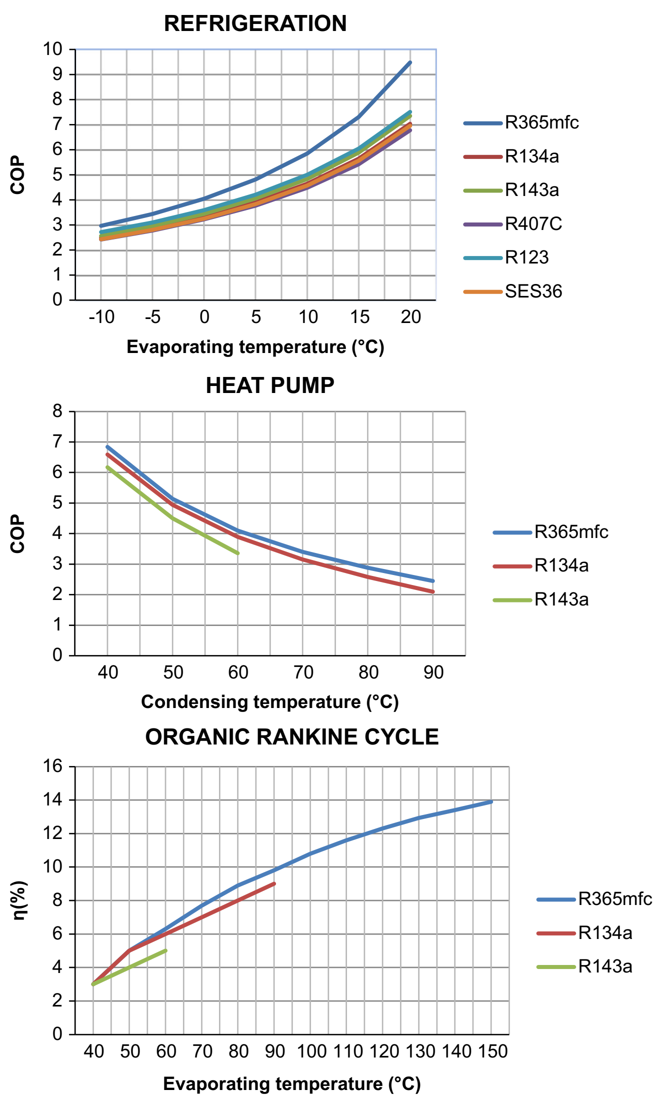

Fig. 14. Fluids performance comparison in different cycles.

and HFO-1234ze [73]. Literature is well documented on criteria for good fluids but appropriate method for the selection is still researched [11,74–78]. Vapor compression refrigeration cycle, heat pump cycle and organic Rankine cycle can be considered as low temperature vapor cycles. They use same working fluids but depending upon highest temperature desired for the cyclic operation, specific characteristics maybe required in agreement with the application. Table 4 gives comparison of criteria. Fig. 14 compares performances of several applications in which organic fluids are involved [75]. It is seen that a fluid suitable for heat pumps could easily be considered for power production in Rankine cycles, but possibly will not yield expected performance in a refrigeration cycle. However, considering these substances adaptable to these low temperature cycles, a new market segment is opening up through organic Rankine cycles. A variety of fluids is available and thus makes a classification possible. In this respect, steam, refrigerant, hydrocarbon and solvent type's machines can be distinguished. With this logic, a conventional power plant would use a water/steam machine, an Electratherm module using R245fa will be considered a refrigerant machine while the triogen module using toluene would be a hydrocarbon engine.

4.1.4. Expansion device

ORC machines sold on the market present different power producing devices. Numerous expanders exist as specially designed for power production as turbines, whereas some are compressors converted. For high power output, turbines are cost-effective and constitute the baseline technology. In the medium to low power of less than 400 kW technical constraints pushed to the development of various expansion devices. Screw, Lysholm or scroll expanders are preferred. Some of these expansion devices are depicted in Fig. 15 [3,35]. The most promising way is to either build a high speed turbine or to convert compressors into expansion devices (or cooling plants into power plants).

4.2. Characteristics of an organic Rankine cycle machine

An organic Rankine cycle machine is characterized by a certain number of input/output parameters that could guide the user when selecting a machine for a specific application. Some of these are listed here below:

T_s	°C	Source temperature
T_{ex}	°C	Exhaust temperature
T_{ev}	°C	Evaporating temperature
M_s	Kg/s	Source mass flow
Q_s	kW	Heat input (evaporator)
M_{wf}	Kg/s	Working fluid mass flow rate
$T_{cm,su}$	°C	Cooling medium temperature supply
$T_{cm,ex}$	°C	Cooling medium temperature exit
T_c	°C	Condensing temperature
M_{cm}	Kg/s	Cooling fluid mass flow rate
Q_c	kW	Heat rejected (condenser)
W_p	kW	Pump power requirement
W_{exp}	kW	Gross power output
W_{net}	kW	Net power output
η_{ORC}	%	System net efficiency

The efficiency of a machine depends on a large number of factors such as maximum acceptable heat source temperature, cooling medium temperature, working fluid thermodynamic

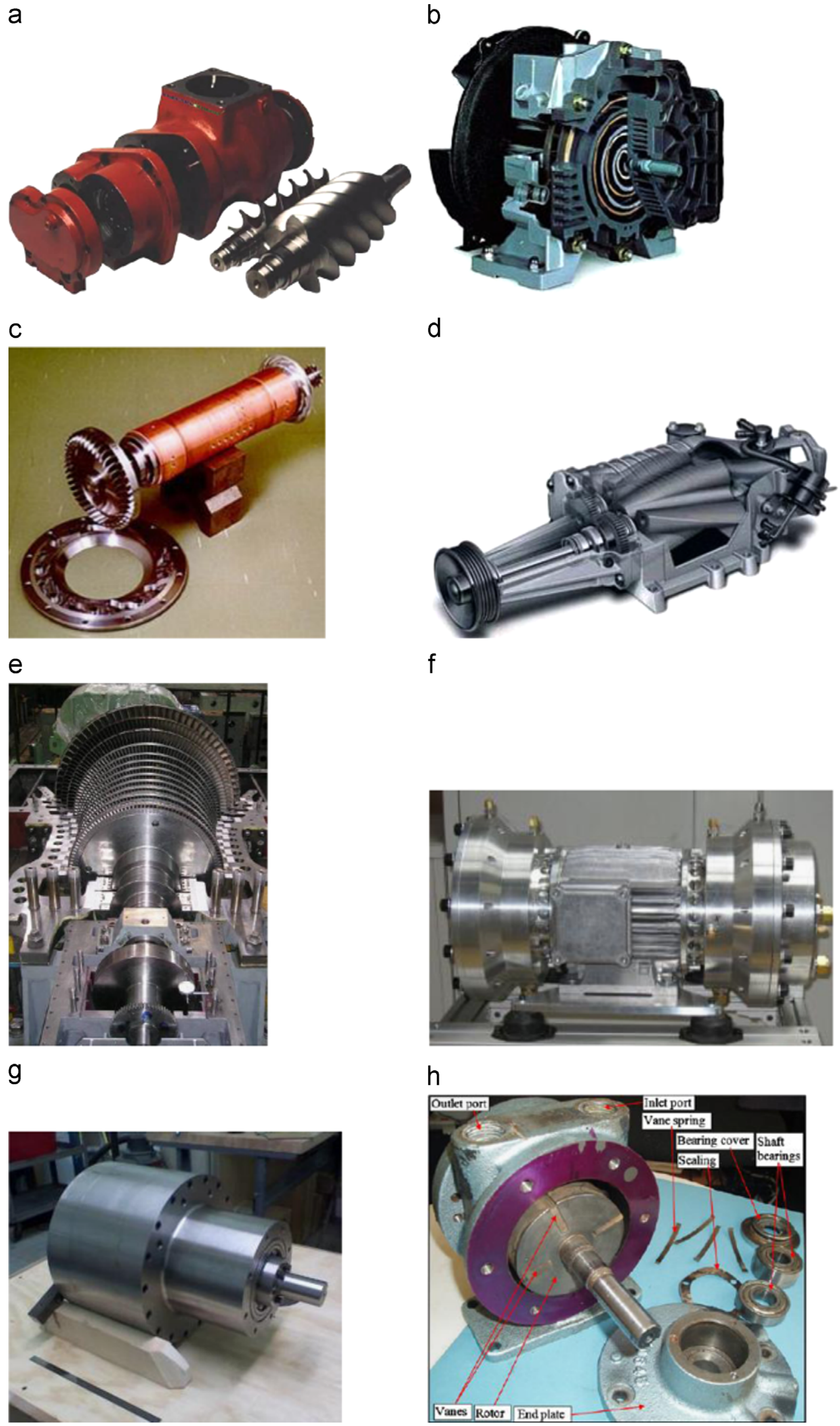

Fig. 15. Various expansion machines. (a) Screw expander, (b) Single stage scroll expander, (c) High speed generator, (d) Lysholm expander, (e) Conventional steam turbine, (f) Double stage scroll expander, (g) Ener-G-Rotors Trochoidal gear engine and (h) vane-type air motor.

parameters, pump efficiency, expansion device efficiency, etc. However, the Carnot efficiency gives a maximum value of the first law efficiency for an ORC machine. A good machine to our opinion should be able to reach at least half of the Carnot limit i.e. the second law efficiency above 50%. As several machines could operate with same sinks and pinch points, and for proper comparison, the second law efficiency can be defined as follows:

$$\eta_{II} = \frac{W_{net}}{Q_s} / \frac{T_{ev} - T_c}{T_{ev}} \quad (1)$$

W_{net} is the net power output, kW, Q_s is the input thermal power, kW, T_{ev} is the evaporator temperature, *K*, and T_c is the condenser temperature, *K*

Considering a condensing temperature of 25 °C, the acceptable limit was found for different evaporation temperature ranging from 50 up to 500 °C. Fig. 16 derived from these considerations shows that a highly efficient machine could have about 25% efficiency. On the market most efficient organic Rankine cycle machines are found in the range 20–25% – see Table 2. Fig. 16 also shows that machines operating in CHP mode will yield lower electrical efficiency as the condensing temperature is taken higher, but the overall efficiency that takes into account the heat recovered at the condenser will be significantly increased, above 80%.

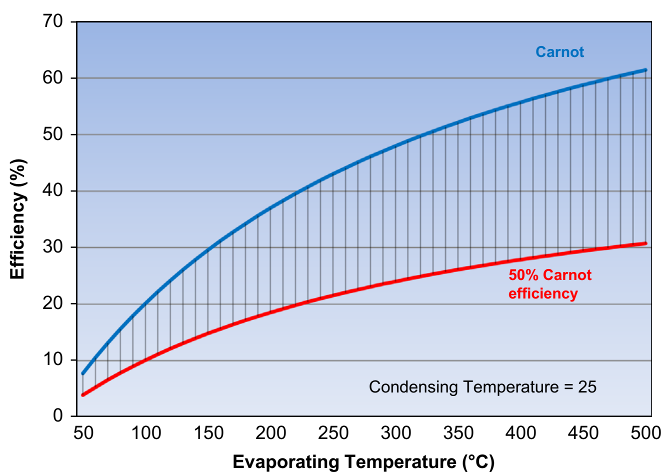

Fig. 16. Thermodynamic limits of an ORC machine.

5. Organic Rankine cycle applications

Solar, biomass and geothermal energy considered as renewable and clean energy sources, and waste heat of any origin can serve as heat sources for organic Rankine cycles as demonstrated in Section 4. The nature i.e. temperature and state of the heat carrier (liquid, solid or gas) influences the engineering design and the economics of the application. However, the aim of an organic Rankine cycle machine is the power generation and as secondary purpose cogeneration or trigeneration with hot water production for heating/cooling. Fig. 17 shows various applications in agreement with heat source temperature and machine type.

Based on previous surveys, some conclusions can recalled [21,61,79]. Geothermal and biomass CHP are mature and cost-effective applications. Modular solar power systems are still under development. OTEC systems are promising for isolated and large islands with minimum acceptable sweater surface temperature. Waste heat recovery application is progressively gaining in popularity; it could help improving the fuel efficiency of stationary and mobile thermal power systems and reduce thermal pollution. Comparison between applications is summarized in Table 5. The key issue when it comes to implement organic Rankine cycle applications is the economics, profitable solutions being always sought especially in times of economic crisis and sometimes at the expense of environmental damages.

Organic Rankine cycle applications vary closely with the type of heat resource available. In all projects there are similar parts like power block, power electronics and transmission/connection components. Heat harvesting systems make the difference among projects. Geothermal projects will require geological investigations of the site, drilling, and appropriate heat exchangers design. Solar projects require site investigation/selection, solar resource assessment, and appropriate solar thermal collectors (usually parabolic troughs), cleaning and cooling systems. Biomass projects need assessment of solid biomass potential in the area/region, investigation of possibility of cogeneration for buildings and eventually the use of heat for industrial processes. Heat recovery projects require good assessment of the heat wasted. In this case, nature of the heat stream, mass flow rate, temperature and availability rate are of significant importance. The investment cost of an ORC project will depend on a set of parameters including size/magnitude of the project, location (latitude, longitude, accessibility, resource, etc.), cost of land (morphology, geology, civil work, etc.),

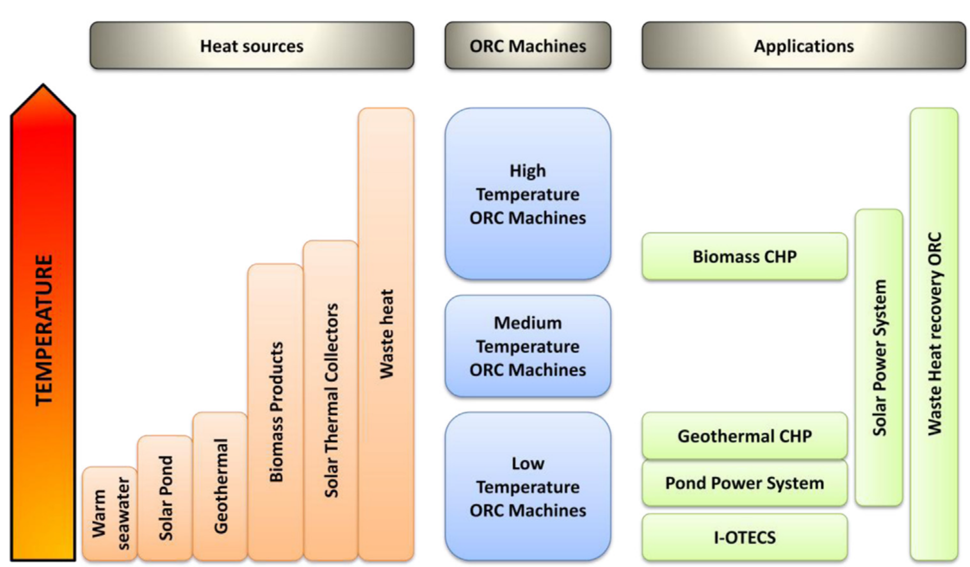

Fig. 17. ORC Applications.

Table 5
Comparison of ORC applications.

Applications	Maturity	Availability factor (%)	Direct GHG emissions	Complexity, operation and maintenance
Geothermal CHP	Mature	70	Very low	Simple
Solar power	Under development	15–25	No	Complex operation and maintenance
Biomass CHP	Mature	70	Yes	Need of fuel, suitable for distributed generation
Waste heat recovery	Very promising	50–60	No	No fuel needed, economics depend on heat availability
OTEC	Promising	80	No	Very low efficiency, large size, high cost and complex

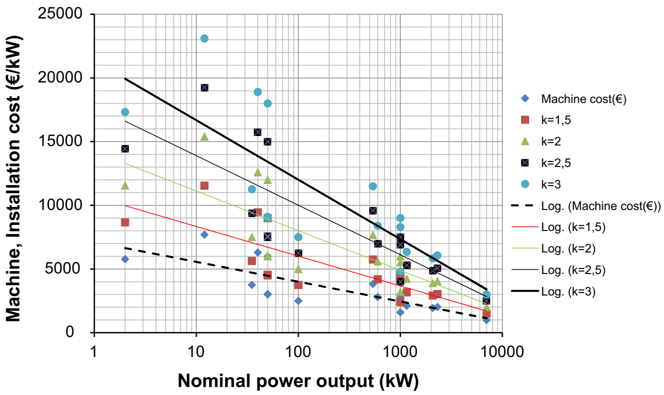

Fig. 18. Machine and installation costs vs nominal power output.

temperature of the heat source, nature of the heat carrier, cost/size of the ORC module, labor, cost of material, capital cost, storage/backup system, etc. The cost of an organic Rankine cycle unit varies depending upon system size, technology and manufacturer [35,79–83]. Specific costs of high temperature machines utilizing toluene and OMTS fluids, and turbines are in the range 1000–3000 €/kW (0.15–2 MWe). Low temperature machines based on refrigerant compressors in reverse mode (scroll, screw) usually show low power output (less than 400 kW), and are more expensive, 1500–2500 €/kW (50–250 kW). Many sources available in literature provide indicative costs of modules [79,84], and considering additional costs due to the engineering and integration of the system, the specific investment cost for the installation is obtained by multiplying the module cost by a coefficient, $k=1.5$–3. Fig. 18 would be useful for a quick estimation of an ORC project. Referring to Quoilin et al. [79], k would be higher for CHP systems and lower for Waste heat recovery systems. It is worth noting that no extensive statistical study has been carried out to approach the reality. Data regarding number of installed systems and capacity by type of application vary in literature from one author to another. Notwithstanding the fact data from well known manufacturers are more reliable, the number of new and very dynamic competitors [68,70,72,85,86] is growing quickly and this should be taken into consideration. Fig. 18 also reveals that small scale systems although very researched is still very expensive, and would therefore be less competitive in comparison with large systems of MW size despite the huge potential they could have, especially in industries for waste heat recovery.

6. Conclusion

Organic Rankine cycle systems have become very popular for heat recovery of various origins. Using another type of working fluid instead of water/steam brings the possibility of manufacturing miniature and portable thermal power plants. The paper recalls various architectures usable. The choice of the architecture will depend on heat source temperature level and type of working fluid, dry or wet. Binary fluid cycles use a mixture of water/ammonia, but are very complex in comparison with Rankine cycles. Heat resources recoverable are industrial waste heat, solar heat, geothermal energy and biomass combustion heat. Potential of these resources have been revealed, and led to enormous potential for recovery using organic Rankine cycles and other technologies. Differences existing among ORC machines are: working fluid type, expander type, size and heat source temperature that will determine the pinch point. Characteristics of a module were recorded: heat source temperature, power output, thermal efficiency, etc. The maximum thermal efficiency of module is found close to 25%. The selection of a module will be primarily based upon application, heat source temperature and desired power output.

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